

## Technology transfer of energy efficient technologies in industry: a review of trends and policy issues

Ernst Worrell<sup>a,\*</sup>, Rene van Berkel<sup>b</sup>, Zhou Fengqi<sup>c</sup>, Christoph Menke<sup>d</sup>, Roberto Schaeffer<sup>e</sup>,  
Robert O. Williams<sup>f</sup>

<sup>a</sup>Energy Analysis Department, Lawrence Berkeley National Laboratory, MS 90-4000, 1 Cyclotron Road, Berkeley CA 94709, USA

<sup>b</sup>John Curtin International Institute, Australia

<sup>c</sup>Energy Research Institute, China

<sup>d</sup>University of Applied Sciences Trier, Germany

<sup>e</sup>Federal University of Rio de Janeiro, Brazil

<sup>f</sup>UNIDO, Austria

Received 23 March 2000

### Abstract

In 1995, industry accounted for 41% of global energy use. Although the efficiency of industrial processes has increased greatly during the past decades, energy efficiency improvements remain the major opportunity to reduce CO<sub>2</sub> emissions. Industrialisation may affect the environment adversely, stressing the need for transfer of cleaner technologies to developing countries. A review of trends, barriers and opportunities for technology transfer is presented. Technology transfer is a process involving assessment, agreement, implementation, evaluation and adaptation, and repetition. Institutional barriers and policies influence the transaction process, as well as the efficiency of the transfer process, in particular in the adaptation and repetition stages of the technology transfer process. Investments in industrial technology are dominated by the private sector. In industry, energy efficiency is often the result of investments in modern equipment, stressing the importance and need for environmentally sound and long-term investment policies. The interactive and dynamic character of technology transfer stresses the need for innovative and flexible approaches, through partnerships between various stakeholders. Adaptation of technology to local conditions is essential, but practices vary widely. Countries that spend on average more on adaptation, seem to be more successful in technology transfer, hence successful technology transfer depends on transfer of technological capabilities. Published by Elsevier Science Ltd.

**Keywords:** Technology transfer; Energy efficient technology; Industry

### 1. Introduction

The industrial sector is extremely diverse and involves a wide range of activities including the extraction of natural resources, conversion into raw materials, and manufacture of finished products. The sub-sectors that account for roughly 45% of all industrial energy consumption, are: iron and steel, chemicals, petroleum refining, pulp and paper, and cement. These industries are generally concerned with the transformation of raw material inputs (e.g., iron ore, crude oil, wood) into usable materials and products for an economy. Due to the wide

variety in activities, energy demand and GHG emissions vary widely. The aggregate energy use and emissions depend on the structure (or specific set of activities) of the industry, and the energy and carbon intensity of each of the activities. The structure of the industry may depend on the phase of the economic development, and many other factors like resource and technology availability as well as historical factors.

In 1995, industry accounted for 41% (131 EJ) of global energy use and up to 43% of global CO<sub>2</sub> emissions (Price *et al.*, 1998). Besides the CO<sub>2</sub> the industry emits also various other GHGs, i.e. CFCs, HFCs, HCFCs, CH<sub>4</sub>, N<sub>2</sub>O, PFCs, CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, and SF<sub>6</sub>. Between 1971 and 1990, industrial energy use grew at a rate of 2.1% per year, slightly less than the world energy demand growth of 2.5% per year. This growth rate of industrial energy use has slowed in recent years, falling to an annual

\* Corresponding author. Tel.: + 1-510-486-5238; fax: + 1-510-486-6996.

E-mail address: Eworrell@lbl.gov (E. Worrell).

Table 1  
Historical energy use in industry (EJ). Primary energy consumption is calculated using a 33% conversion efficiency for electricity generation for all years and regions. Source: Price *et al.* (1998)

Region	Total industrial energy use (EJ)					Average annual growth rate (%/annum)		
	1960	1971	1980	1990	1995	1960–1990	1971–1990	1990–1995
OECD	28	49	55	54	57	2.3	0.6	0.9
EE-FSU		26	34	38	26		2.0	– 7.3
Developing countries		13	24	37	48		5.4	5.0
World		88	114	129	131		2.1	0.2

average growth of 0.2% between 1990 and 1995, primarily because of declining industrial output in the economies in transition. Energy use in the industrial sector is dominated by the OECD countries, which account for 44% of world industrial energy use. Non-Annex-1 countries and countries with economies in transition (CEITs) use 37 and 20% of 1995 world industrial energy, respectively. Industrial production is growing at a fast rate in Non-Annex-1 countries. The trends in industrial energy use are given in Table 1.

Industrial production is an important engine to increase the economic activity, generate employment, and build up the infrastructure in developing countries. Investment in industry seems to have a stronger relation with economic growth than investments in other sectors (UNIDO, 1997). This can also be observed from the growing importance of industry in a developing nation's economy and contribution to the growth (UNIDO, 1997). High industrial growth also promotes technological change (UNIDO, 1997). Capital investment in industry is important to achieve economic welfare in developing countries. Capital relates to physical (e.g. equipment), human (e.g. education) and technological capital (e.g. science, R&D).

Industrialisation builds on the contribution of science and technology, as is evidenced by the Chinese economic development in the past decades (Song, 1997). However, industrial technology should fit to the needs of the users in developing economies. Technologies developed for a specific industrial infrastructure (e.g. raw materials used (UNEP, 1997), relative shares of production costs) may not always be the right choice for an other, as is shown by examples of failed applications of industrial technology in Tanzania (Yhdego, 1995) and India (Schumacher and Sathaye, 1998). Adaptation and development of technology to suit the needs is an essential step in successful transfer of technology. Hence, technology transfer is a process involving the trade and investment in technology, the selection (e.g. new, second-hand), adoption, adaptation, and dissemination of industrial technology, and last but not least capacity building, as science and technology are strongly related (Song, 1997) in the development of an industrial infrastructure.

Future growth of basic industries will, to a large extent, occur in developing countries. While developing countries are the most important markets for new and energy efficient processes, technology is still primarily developed in industrialised countries, despite the fact that the absolute demand for such technologies is stagnating or relatively low. Industrialised countries will be less favourable theatres for innovation of technologies for the primary materials processing industries, if there are limited applications for such in industrialised countries. However, investments in materials processing industries in developing countries are most often made by or on behalf of transnational corporations headquartered in industrialised countries, and facing peer, and sometimes even shareholder, pressure to adopt equally innovative technologies for their business ventures in developing countries. Moreover, several Annex B countries to the Kyoto Protocol have significant potential to further develop their primary resources industries, but will in light of the emission targets agreed, only be able to exploit such potential, through the application of energy efficient, low carbon technologies, which in turn is a strong driver for RD&D and investment in such technologies. There is a strong need, both for technology adaptation to the prevailing conditions in developing countries, and intensified collaboration between suppliers and users of new industrial processes. The rapidly increasing role of transnational companies, and foreign direct investment (UNCTAD, 1997), may change the patterns of technology transfer. The trend towards globalizing industries as well as transboundary environmental issues will likely impact technology transfer in such a way that transfer of technology within and between countries will meet similar barriers and challenges.

Technology transfer needs to be studied within these perspectives. It seems that environmentally sound technologies do not transfer as rapidly as e.g. information technology, particularly with regard to developing countries. These issues warrant a specific study of transfer of environmentally sound industrial technology, with an emphasis on GHG abatement technologies. We describe the experiences with various forms of technology transfer. Technology transfer is defined as the transfer and

development of ‘hardware’ and ‘software’. The ‘software’ may include scientific and engineering knowledge as well as managerial and operational skills. After a brief summary of the technologies for GHG mitigation, we discuss the trends in technology transfer from an economic perspective, and study magnitude and directions, as well as sources of investment and technology. In the next section we study the processes of technology transfer between and within countries, assessing barriers and opportunities for technology transfer, based on international experiences. This is followed by an evaluation of the analysed material and description of the main lessons learned.

## 2. Technology options for energy efficiency improvement

Energy efficiency improvement is technologically feasible for the industrial sector of OECD countries if technologies comparable to the present generation efficient industrial facilities are adopted during stock turnover. For Annex I countries with economies in transition, efficiency improvement options are intimately tied to the economic redevelopment choices and the form that industrial restructuring takes. In developing countries large potentials for adoption of energy and resource efficient technologies exist as the role of industry is expanding in the economy.

Although the efficiency of industrial processes has increased greatly during the past decades, major opportunities for energy efficiency improvements remain. Efficient use of materials may also offer significant potential for reduction of energy use and GHG emissions (Gielen, 1998; Worrell *et al.*, 1997). Much of the potential for improvement in technical energy efficiencies in industrial processes depends on how closely such processes have approached their thermodynamic limit. For industrial processes that require moderate temperatures and pressures, such as those in the pulp and paper industry, there exists long-term potential to maintain strong annual intensity reductions. For those processes that require very high temperatures or pressures, such as crude steel production, the opportunities for continued improvement are more limited. New process schemes, resource efficiency, substitution of materials, changes in design and manufacture of products resulting in less material use and increased recycling, can lead to substantial reduction in energy intensity. Furthermore, switching to less carbon-intensive industrial fuels can reduce energy use in a cost-effective way (Worrell *et al.*, 1997). In addition, there are many low-cost actions that can be adopted as part of good management practices. Table 2 provides a summary of categories and examples of energy efficient technologies and practices in the industrial sector (based on WEC (1995), and Worrell *et al.* (1997)).

## 3. Trends in technology transfer

As countries develop from an agrarian society to an industrial urban economy the economic structure of a developing nation goes through a transition process, as described by Kuznets (1971). The structure of the economy is strongly dependent on the stage of development, and hence the technology needs (Syrquin and Chenery, 1988). The transition process may not be smooth (especially over short periods), and may follow various paths. Syrquin and Chenery (1988) showed that the performance of the economy is associated with large size, manufacturing orientation and with a higher degree of openness. The smaller the economy, the more it relies on the open character of the economy. However, alternative paths may be successful too, as evidenced by the development of economies like South Korea, where industries matured under economic protection (Lee, 1997).

The rate of technological change strongly affects the rate of investment and the productivity and vice versa. Investment in modern equipment, evidenced by the economic growth in newly industrialized economies in East Asia, is seen as a more important contribution to growth than other investments (UNIDO, 1997). The growing industrial production in Asia, especially China (5% of world manufacturing value added (MVA) in 1995), is shown in Fig. 1. Fig. 1 shows that world MVA is still dominated by the industrialized countries, while MVA of the economies in transition decreased. The share of other regions in world MVA did remain stable. The importance of the industrial sector in the regional economy is increasing in most developing regions.

Although the growth pattern of the industrial sector may differ between countries, generally the growth is associated with the use of capital intensive technology for e.g. the raw material based industries. Brazil, China, India (Kaplinsky, 1997) and Korea are examples of this pattern, though in different stages of development. However, there is considerable debate about the importance of the industrial sector in the economic development process. Growing importance of the services sector in some developing economies (Asia, Latin America) generates an increasingly larger part in economic growth (World Bank, 1998).

The trends in industrial investments are difficult to translate to technology choice and transfer. It is obvious, though, that increasing international investments influence the rate of technology transfer, although it gives no information on the way and what technology is transferred. Generally, the majority of investments in many developing countries seem to be in low-technology industries, though the share of high-technology industries is increasing (UNIDO, 1997). There is no hard information available on the role of the markets for environmentally sustainable technologies (including energy efficiency) (Luken and Freij, 1995). We use

Table 2  
Categories and selected examples of practices and technologies to mitigate GHG emissions in the industrial sector, based on SAR II, WEC (1995), Worrell et al. (1997)

Option	Measures	Climate and other environmental effects	Economic and social effects	Administrative, institutional and political considerations
<b>End-use</b>				
<b>Energy efficiency gains</b>	–Market mechanisms	–Savings on CO <sub>2</sub> emissions	–Highly cost-effective	–Major effort from industry
–More efficient end-uses	–Voluntary agreements	–Reduction of air pollution	–Restructuring tax system to taxing resource use	–Change regulatory and tax systems
–Reduction of energy losses	–Energy price reform		–Equity issues in providing energy services	–Coordination
	–Information programs			–International coordination and monitoring
	–International corporation			–Major effort from industry
<b>Process improvement</b>	–Voluntary agreements	–Savings on CO <sub>2</sub> and non-CO <sub>2</sub> GHG emissions	–Highly cost-effective	–See above
–Process integration	–Regulatory measures	–Reduction of air pollution		
–Reduction non-CO <sub>2</sub> emission				
<b>New technologies and processes</b>	–RD&D	–Savings on CO <sub>2</sub> and non-CO <sub>2</sub> GHG emissions	–R&D investments	–Funding
–New production technologies, e.g. steel, chemicals, pulp	–International corporation	–Reduction of air pollution	–Cost-effective on the long-term	–Industry, academic and government labs
			–Transform industrial infrastructure and basis	–Modest changes in administrative factors
<b>Conversion</b>				
<b>Cogeneration</b>	–Voluntary agreements	–Reduction in CO <sub>2</sub> emissions	–Highly cost-effective	–Major effort from industry
–CHP using gas turbines, fuel cells	–Regulatory measures	–Reduction in air pollution	–Some industry restructuring (PPI)	–Changes in regulatory regimes
	–Market mechanisms			–Siting for optimal use
	–RD&D			
<b>Fuel switching</b>	–Regulatory measures	–Reduction in CO <sub>2</sub> emissions	–Highly cost-effective	–Major effort from industry
–Natural gas		–Reduction in air pollution	–Internalizing external costs may hasten shift	–Opposition of producers fuels being displaced
–Biomass			–Trade-off with other uses (e.g. biomass)	
–Solar (drying, water heating)				
<b>Material use</b>				
<b>Efficient material use</b>	–Voluntary agreements	–Reduction in CO <sub>2</sub> emissions	–Highly cost-effective	–Major effort from industry
–Efficient design	–Market mechanisms	–Reduction in air pollution	–Decreased use of primary resources	–Engage all actors in problem solving
–Substitution	–Regulatory measures	–Reduction in solid waste and primary resource use	–Dislocations in existing industry	–Regulatory changes
–Recycling	–RD&D		–Job creation near product users	–Opposition to regulatory changes
–Material quality				
Cascading				

investment flows as a proxy for investments and technology transfer. While recognizing that investment flows do not consider differences in the ‘quality’ of investments made, there seems to be no other simple indicator for the magnitude of technology transfer taking place.

### 3.1. International investment patterns

Recent trends in industrial development stress the openness in trade and investments. Today, foreign direct

investment (FDI) and joint ventures (JV) by transnational corporations (TNC) are the largest foreign investments in industrial development in developing countries (UNCTAD, 1997). FDI aims at accessing and developing markets, whereas portfolio equity investment (PEI) is more directed to participating in local enterprises. Following the globalization trend PEI is also growing, but tends to be more centred on developed markets and to be more fluid. PEI is estimated at US\$ 45 billion (1995) (UNCTAD, 1997) (Fig. 2). Foreign capital accounts for

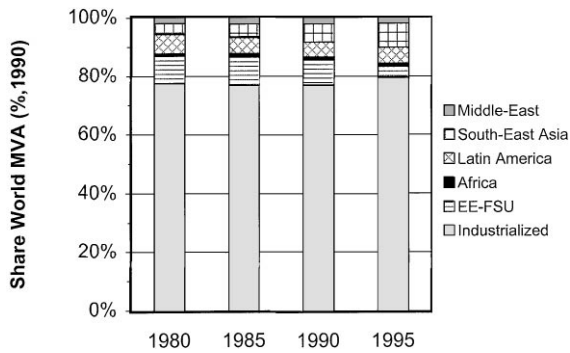


Fig. 1. Regional shares of world manufacturing value added (MVA). Source: IPCC, 2000.

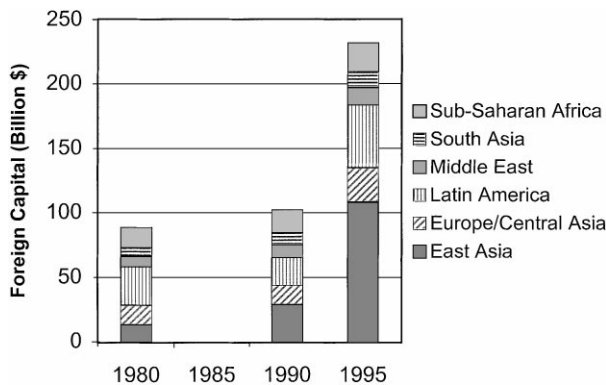


Fig. 2. Foreign capital investment (billion US\$) in developing countries, by region. Source: IPCC, 2000.

only 6% (1995) of total investments in developing countries (UNIDO, 1997). In developing countries public spending is responsible for about a quarter of income (World Bank, 1997a) although the role played by public spending has declined relatively over the past 25 years (UNIDO, 1997).

Transnational corporations spending in international investments increased from less than US\$100 billion in the early 1970s to over US\$1.4 trillion in 1996 (UNCTAD, 1997). The majority of the funds is still spent in industrialized countries, but an increasing part is spent in developing countries. Fig. 3 shows that foreign industrial capital spending is concentrated in two regions, East Asia and Latin America. These regions have experienced successful industrial growth in the last decade, although concentrated in a few countries. FDI, a part of the international investments, has grown to US\$350 billion in 1996 (UNCTAD, 1997), of which 34% (US\$ 119 billion) was invested in developing countries (see Fig. 3). Future trends in FDI seem to sustain, as international trade seems to gain in importance, and as countries are liberalising trade and investment.

Previous periods of high growth in FDI were mainly directed to oil-producing countries. The current growth of FDI seems to be more diverse, although there is

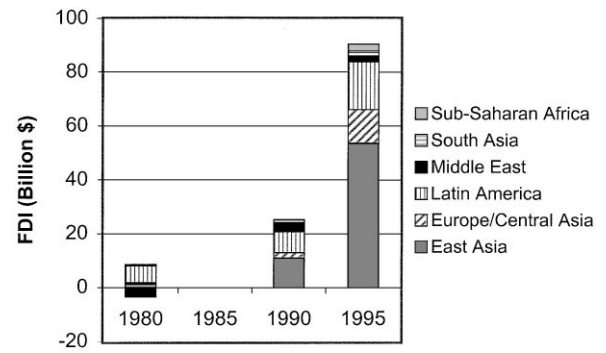


Fig. 3. Foreign direct investment (billion US\$) in developing countries, by region. Source: IPCC, 2000.

a strong geographic concentration. Of the \$129 billion FDI in developing countries, \$42 billion was spent in China, followed by Brazil (US\$10 billion) (UNCTAD, 1997). Favoured regions are Asia and Latin America, and there are signs of increasing FDI in Africa, although still limited. Important is the increasing FDI from developing countries, especially Asia, which increased to US\$52 billion in 1996 (UNCTAD, 1997). In Asia regional investments seem to be the main driver for industrialisation. FDI in the former Central and Eastern Europe are relatively constant at US\$12–14 billion, but also concentrated in a few countries (e.g. Poland, Czech Republic).

FDI is concentrated in a relatively small number of TNCs. The top 100 TNCs contains only a few TNCs based in developing countries, although growing in importance. TNCs seem to be most important in the electronics, automotive, and chemical industries, as well as petroleum and mining. TNCs seem to be more productive than domestic companies (UNIDO, 1997), which may be partly due to more efficient production technologies and practices used. The role of TNCs in industrial development is generally seen as positive, although negative effects may arise from TNC involvement if the market power of the TNC is high.

*Other capital flows* are declining in relative and absolute sense. Annual official development assistance (bilateral and multilateral) averaged about US\$60 billion since 1990 (UNIDO, 1997), of which less than 10% is invested in industrial development. Approximately, 2% of bilateral and 6% of multilateral aid is spent in industrial development (UNIDO, 1997). Major recipients of development aid earmarked for industry are low-to-medium income countries, e.g. Bangladesh, China and Indonesia. Other financial flows include development loans and export credits, used primarily to finance the export of capital goods and equipment. Export credits and loans seem to be heavily concentrated in large low-income but creditworthy countries, and increasingly in countries that have (gained) access to international financial markets. The majority of low-income developing countries have no access to these funds.

Scientific and technical capability are key to the economic and industrial development of developing countries (Rama Rao, 1997; Song, 1997; Suttmeier, 1997). Direct investment in industrial R&D may be included in the investment figures discussed above. The R&D funds allocated to environmentally sound technologies (ESTs) are only a small part of the total industrial technology R&D budget. Energy R&D budgets of OECD countries have declined in past decades. In the recent past, less than 6% of the total energy R&D budget in IEA countries was spent on energy efficiency (IEA, 1994). Also scientific knowledge and R&D are getting more and more internationally oriented, as evidenced by FDI in R&D. It is estimated that foreign corporation spending in the US in 1994 amounted to US\$15 billion, or 15% of total industrial R&D spending (Florida, 1997). Generally, FDI in R&D is comparatively small, mostly directed to support local industry. FDI in R&D is growing rapidly, particularly in the US (Florida, 1997). International R&D collaboration can be an effective means of technology transfer. Preliminary analysis seems to suggest that newly industrialized countries seem to increase the generation of scientific and technological knowledge in the countries, although the majority of knowledge is still generated in the industrialized world (Amsden and Mourshed, 1997). No accurate information is available on the global role of and investments in scientific knowledge in developing countries.

#### 4. Barriers to technology transfer

Although technology transfer is often seen as a private interaction between two companies or trade partners, institutional barriers and policies influence the transaction process, as well as the efficiency of the transfer process. Under perfect market conditions, all additional needs for energy services are provided by the lowest cost measures, whether energy supply increases or energy demand reductions. There is considerable evidence that substantial energy efficiency investments that are lower in cost than marginal energy supply are not made in real markets, suggesting that market barriers exist. A wide body of literature discusses the barriers that affect implementation and diffusion of technologies (see for a review: Worrell *et al.*, 1997). We concentrate on the experiences of programmes with respect to environmental and energy efficient technologies in developing countries and CEITs. Developing countries and CEITs suffer from all barriers that inhibit technology transfer plus a multitude of other problems. Increasing globalization of industry is changing the roles of different stakeholders. Ultimately, this will lead to a global market for technology with similar types of barriers between and within countries. Below we discuss several categories of barriers to technology transfer.

*Decision-making processes* in firms are a function of their rules of procedure, business climate, corporate culture, managers' personalities and perception of the firm's energy efficiency (DeCanio, 1993; OTA, 1993). Rigid hierarchical structure of organisations and the paucity of organisations occupying the few niches in a given area lead to strong and closed networks of decision makers who are often strongly wedded to the benefits they receive from the status quo (see e.g. Gadgil and Sastry (1994) for an example of efficient lighting systems). Energy awareness as a means to reduce production costs seems not to be a high priority in many firms, despite a number of excellent examples in industry, e.g. (Nelson, 1994). Cost-effective energy efficiency measures are often not undertaken as a result of *lack of information* on the part of the consumer, or a lack of confidence in the information, or high transaction costs for obtaining reliable information (Reddy, 1991; OTA, 1993; Levine *et al.*, 1995; Sioshansi, 1991). Information collection and processing consumes time and resources, which is especially difficult for small firms (Gruber and Brand, 1991; Velthuisen, 1995). In many developing countries and CEITs public capacity for information dissemination is lacking, stressing the need for training in these countries, and is seen as a major barrier for technology transfer (TERI, 1997). The problem of the information gap concerns not only consumers of end-use equipment but all aspects of the market (Reddy, 1991). Many producers of end-use equipment have little knowledge of ways to make their products energy efficient, and even less access to the technology for producing the improved products. End-use providers are often unacquainted with efficient technology. In addition to a lack of information at least two other factors may be important, i.e. a focus on market and production expansion, which may be more effective than efficiency improvements, to generate profit maximisation, and the lack of adequate management tools, techniques and procedures to account for economic benefits of efficiency improvements.

*Limited capital availability* will lead to high hurdle rates for energy efficiency investments because capital is used for competing investment priorities. Capital rationing is often used within firms as an allocation means for investments, leading to even higher hurdle rates, especially for small projects with rates of return from 35 to 60%, much higher than the cost of capital (~ 15%) (Ross, 1986). In many developing countries industries have even more difficult access to capital and the cost of capital for domestic enterprises is generally in the range of up to 30–40%. When energy prices do not reflect the real costs of energy (without subsidies or externalities), then consumers will necessarily under invest in energy efficiency.

High inflation rates in developing countries and CEITs, lack of sufficient infrastructure increase the risks for domestic and foreign investors and limit the availability of capital. Lack of capital may result in the purchase

of used industrial equipment (Sturm *et al.*, 1997), resulting in higher energy use and/or GHG emissions, as well as higher production costs. Trade in second-hand industrial equipment to developing countries and CEITs is quite common in most industrial sectors. National trade and investment policies may limit the inflow of foreign capital. This might be a barrier to technology transfer. Recent liberalisation of investment regimes, in e.g. the mining industry, is seen as a way to transfer and acquire new technologies and reduce environmental damage (Warhurst and Bridge, 1997). This also applies to the role of TNCs and their role in technology transfer. The technology co-operation to phase out the use of ozone-depleting gases in the manufacture of semiconductors in the Global Semiconductor Partnership provides an example of co-operation between TNCs as a way to improve access of knowledge and technologies within a more liberalised market, and a way to avoid command and control regulations (IPCC, 2000).

Energy prices, and hence the profitability of an investment, are also subject to large fluctuations. The uncertainty about the energy price, especially in the short term, seems to be an important barrier (Velthuisen, 1995). The uncertainties often lead to higher perceived risks, and therefore to more stringent investment criteria and a higher hurdle rate.

Research in developing countries shows that especially small- and medium-sized enterprises (SMEs) contribute for a large part to industrial employment, and that in LDCs industrial employment is found mainly in rural areas (Little, 1987; Putterman, 1997; UNIDO, 1997). However, this does not necessarily mean that SMEs are more efficient with regard to capital and resource use (Little, 1987). There is growing evidence that SMEs in some countries may be less efficient with respect to resource use (World Bank, 1997b). However, there is also a growing number of examples of innovative SMEs — often producing for export markets — that outperform their local, large-scale competitors, in particular, state-owned large-scale enterprises (Berkel and Bouma, 1999). Sound market conditions are crucial to create a competitive market in which innovation by SMEs in process technology is stimulated. Especially for SMEs capital availability may be a major hurdle in investing in energy efficiency improvement technologies due to limited access to banking and financing mechanisms. SMEs have less access to international financing, and hence rely more on domestic capital and public spending. Even small investments in cleaner production and GHG abatement projects in SMEs are often not done, due to lack of capital, poorly developed banking system, lack of appropriate financing mechanisms, lack of knowledge (both within the industry as the financial sector), technology risks, and management's unwillingness to borrow funds (Berkel and Bouma, 1999). For example, township and village enterprises (TVEs) in China do not have

access to capital, because (until recently) only two banks were allowed to have branches in rural areas, while lending was also difficult due to the lack of proper internal procedures and lack of sufficient securities. These barriers reduce the availability of capital, stimulating investors to keep investment costs low, which may result in purchase of second-hand equipment, low-quality products, or equipment without modern controls and instrumentation. Lack of access to capital and credit is seen as the strongest barrier to development of SMEs (UNIDO, 1997). Various developing countries have experimented and applied financing schemes for SMEs, e.g. Ecuador, Indonesia, Korea, Malaysia, Pakistan and Tanzania, with varying rates of success. The examples above show that the success of credit provision is dependent on the establishment of a technological, management and institutional structure to support and monitor the performance of SMEs, and that managerial support is necessary on the highest level (UNIDO, 1997).

*Information on and assessment of technologies* provided by foreign suppliers is more difficult for local investors in developing economies. Dependence on foreign suppliers may also induce risks in the case of technological support. For almost all industries the major suppliers can be found in the industrialised world, although some developing countries (e.g. Brazil, China, India) or sectors (e.g. sugar cane processing) develop and supply indigenous and even advanced technologies (e.g. Brazil, South Korea) as well. Experience has shown that environmental considerations should be more carefully integrated into development and co-operation policies. The policies in technology producing countries for transfer of environmentally sound technologies to developing countries seem to be inadequate (UN, 1998). In developing countries and CEITs a lack of protection of intellectual property rights may exist, which is seen as a barrier by technology suppliers (UN, 1998). Also, technology licensing-procedures may be time consuming, leading to high transaction costs. Besides the problems with technology selection and supply, inadequate environmental policies, and particularly lacking regulation and instruments for implementation thereof, in developing countries and CEITs will reduce the demand for such technologies.

In many firms there is often a *shortage of trained technical personnel*, as most personnel are busy maintaining production (OTA, 1993). In the CEITs the disintegration of the industrial conglomerates may lead to loss of expertise. Lack of skilled personnel, especially for SMEs, leads to difficulties installing new energy-efficient equipment compared to the simplicity of buying energy (Reddy, 1991; Velthuisen, 1995). In China, TVEs rely on low-grade, non-standardised technologies owing to their origins as commune-based, non-sector specialist enterprises. Their establishment outside the sector-specialist line ministries gave them little access to the traditional

mechanisms promoting technological advancement in China. TVEs have limited interchange with technology suppliers and only sporadic contact with public bureau and sector-specialist line ministries. Current acquisition patterns do not adequately take into account the conditions of production within TVE, leading to the poor integration of system components and low performance. TVE staff is often not qualified to operate and maintain the new equipment properly.

In addition to the problems identified above, other important barriers include (1) the ‘invisibility’ of energy efficiency measures and the difficulty of demonstrating and quantifying their impacts; (2) lack of inclusion of external costs of energy production and use in the price of energy, and (3) slow diffusion of innovative technology into markets (Levine *et al.*, 1994; Fisher and Rothkopf, 1989; Sanstad and Howarth, 1994). Regulation can, sometimes indirectly, be a barrier to implementation of low GHG emitting practices. A specific example is industrial cogeneration, which may be hindered by the lack of clear policies for buy-back of excess power, regulation for standby power, and wheeling of power to other users. Cogeneration in the Indian sugar industry was hindered by the lack of these regulations (WWF, 1996). The existence of clear policies can be a driver for diffusion and expansion of industrial cogeneration, as is evidenced by the development of industrial cogeneration in The Netherlands (Blok, 1993). In addition, alternative models may be found important in focusing public policy on the need to raise end-user awareness and priority to increased energy efficiency. This is likely to be an effective route to ensuring industry takes a comprehensive view of energy efficiency.

## 5. Programmes and policies for technology transfer

In this section we will follow the steps in the transfer process, using experiences reported in the literature. The steps we follow are: assessment, agreement, implementation, evaluation and adaptation, and repetition. Fig. 4 gives a schematic representation of the process. Various programmes try to lower the barriers simultaneously in some steps. A wide array of policies, to increase the implementation rate of new technologies, has been used and tested in the industrial sector, with varying success rates. We will not discuss general programmes and policies, but concentrate on specific examples in the industrial sector, with an emphasis on developing countries experiences. Technology diffusion is influenced by many parameters, including capital costs, resources, productivity and resource efficiency. With respect to technology diffusion policies there is no single instrument to reduce barriers; instead, an integrated policy accounting for the characteristics of technologies, stakeholders and countries addressed is needed.

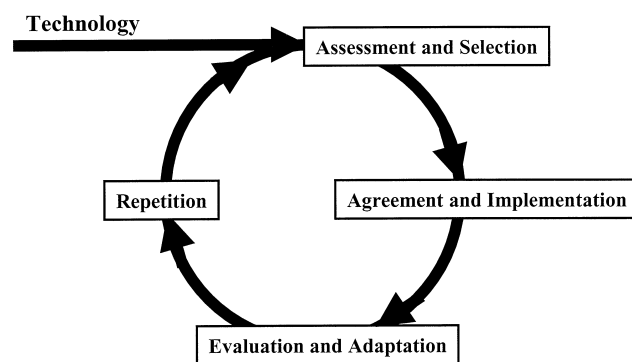


Fig. 4. Schematic representation of the analysis steps in technology transfer processes.

Energy efficiency and GHG emission abatement should be viewed as an integral component of national and international development policies. Energy efficiency is commonly much less expensive to incorporate in the design process in new projects than as an afterthought or a retrofit. In the environmental domain, we have learned that “end of pipe” technologies for pollutant clean-up are often significantly more expensive than project redesign for pollution prevention, leading to widespread use of pre-project environmental impact statements to address these issues in the planning phase. Energy efficiency should also be incorporated into the planning and design processes wherever there are direct or indirect impacts on energy use such as in the design of industrial facilities, reducing the costs for energy supply and reducing the risks of local air pollution. This has not always been the case, as shown by Callin *et al.* (1991) for the investment in a new paper mill in Tanzania.

Most policies and programmes for transfer of environmentally sound and greenhouse gas abatement technologies are national, and only a few are internationally oriented. Most industrialized (donor) countries have policies in place, but strongly connected to (technology) interests of the donor country. Joint implementation or activities implemented jointly (JI/AIJ) may also be a useful energy efficiency promotion instrument. JI involves a bi- or multi-lateral agreement, in which (donor) countries with high greenhouse gas abatement costs in implementing mitigation measures in a (host) country with lower costs, and receive credit for (part of) the resulting reduction in emissions. Under COP-3 the clean development mechanism (CDM) has been introduced as means to accelerate emissions reduction and credit emission reductions from project activities in non-Annex-1 countries to Annex-1 countries. The criteria for JI/CDM are still in the process of development (Goldemberg, 1998). Most likely the projects should fit in the scope of sustainable development of the host country (without reducing national autonomy and with co-operation of the national government), have multiple (environmental) benefits, be

selected using strict criteria and be limited to a part of the abatement obligations of a donor country (Jepma, 1995; Pearce, 1995; Jackson, 1995). Determination (and crediting) of the net emission reductions is a problem that stresses the need of well-developed baseline emissions (La Rovere, 1998), i.e. emissions that would occur in the absence of the project (Jackson, 1995). JI/CDM can prove to be a viable financing instrument to accelerate developments in economies-in-transition and in developing countries, if implemented according to specific criteria as outlined by Goldemberg (1998). However, with current shadow prices for CO<sub>2</sub>, CDM is unlikely to substantially increase investment in ESTs. Comprehensive evaluation of pilot projects is necessary to formulate and adapt these criteria including the issue of crediting.

### 5.1. Assessment

Selection of technology is a crucial step in any technology transfer. Information programmes are designed to assist energy consumers in understanding and employing technologies and practices to use energy more efficiently. These programmes aim to increase consumers' awareness, acceptance, and use of particular technologies or utility energy conservation programmes. Examples of information programmes include educational brochures, hotlines, videos, design-assistance, audits, and labelling programmes. Information needs are strongly determined by the situation of the actor. Therefore, successful programmes should be tailored to meet these needs. Surveys in Germany (Gruber and Brand, 1991) and The Netherlands (Velthuisen, 1995) showed that trade literature, personal information from equipment manufacturers and exchange between colleagues are important information sources. In the United Kingdom, the 'Best Practice' programme aims to improve information on energy efficient technologies, by demonstration projects, information dissemination and benchmarking. The programme has been effective in achieving cost-effective energy savings, and is now replicated in various countries (Collingwood and Goult, 1998). In developing countries and CEITs technology information is more difficult to obtain. These efforts to collect and distribute data seem to be successful, and have led to the establishment of visions on technology development in e.g. China and India (TERI, 1997).

Energy audit programmes are a more targeted type of information transaction than advertising. Industrial customers who received audits reduced their electricity use by an average of 2–8%, with the higher savings rates achieved when utilities followed up their initial recommendations with strong marketing, repeated follow-up visits (Muller and Barnish, 1998), and financial incentives to implement the recommended measures (Nadel, 1990, 1991). Energy audit programmes exist in numerous

developing countries, and an evaluation of programmes in 11 different countries found that, on average, 56% of the recommended measures were implemented by audit recipients (Nadel *et al.*, 1991). The Indo-German Energy Efficiency Project in Indian industries confirms that 50–60% of the recommendations were implemented, resulting in energy savings of 5–15%. Moreover, energy auditing proved to be a viable self-sustaining business opportunity, as the Indian partner was well equipped and motivated (IPCC, 2000).

Technology assessment and selection is very important. However, often the capacity is missing, or the selected technology is determined by a donor country or by available financing (e.g. bilateral export loans or tight aid). This may lead to sub-optimal technology choices (Schumacher and Sathaye, 1998; Yhdego, 1995). An important arena for co-operation between the industrialised and developing countries involves the development and strengthening of local technical and policy-making capacity, for example for an assessment of (technical) needs. Large companies may be able to access information or resources or hire engineering companies more easily, like in the chemical industry (Hassan, 1997). SMEs and local companies have generally less easy access to external resources. Project-oriented agencies eager to show results commonly pay inadequate attention to the development of institutional capacity and technical and managerial skills needed to make and implement energy efficiency policy. The Japanese Green Assistance Plan aims at supporting Japanese exports of energy efficient technologies to other Asian countries, including China and Thailand (Sasaki and Asuka-Zhang, 1997). Hu *et al.* (1998) report on the transfer of dry coke quenching technology from Japan to China as part of the Japanese Green Assistance programme and JI/AIJ. The recipient, Capital Steel, had no choice in the technology selection, as the transfer was the product of co-operation of both governments. Projects in India (TERI, 1997), as well as Leadership Programmes under the Montreal Treaty in Thailand and Vietnam, aimed at the development of the needed capacity. The Indian projects proved to be successful, in the sense that they built active capacity assessing needs and opportunities for energy efficiency improvement and clean technologies for industries in various regions. Formal recognition of the acquired skills in knowledge transfer seems to be important to improve the status of a programme. International partnerships of firms can be a successful tool to transfer technologies, as shown in the Vietnam Leadership Programme between various TNCs active in Vietnam and government agencies to phase out the use of CFCs in the Vietnamese electronics industry. The example of bi-lateral co-operation between US electronics manufacturers and Mexican suppliers helped to overcome some of the barriers in information supply and access to technology and financing (IPCC, 2000).

As industrial development increases, capabilities for technology assessment and selection improve, as evidenced by investment projects in modern cement plants in India (Somani and Kothari, 1997), Mexico (Turley, 1995) and Taiwan (Chang, 1994). This stresses that development of technical capabilities is a continuous process, because it takes large resources to build up a knowledge infrastructure, and the key to success is the so-called ‘tacit knowledge’ (unwritten knowledge obtained by experience) (Dosi, 1988), which is easily lost. The greater the existing capability, the greater the opportunities are for gaining knowledge from industrial collaboration and technology transfer (Chantramonklasi, 1990). Finally, language can be a barrier in successful transfer of a technology, especially when working with local contractors or suppliers (Hassan, 1997).

### 5.2. *Agreement and implementation*

Actual implementation of technologies and practices depends on the motivation of management and personnel, external driving forces (e.g. voluntary agreements, legislation and standard setting), economics (i.e. profitability), availability of financial and human resources. Environmental legislation can be a driving force in the adoption of new technologies, as is the case in India (TERI, 1997) and the process for uptake of environmental technologies in the US (Clark, 1997). Higher energy prices can increase the implementation rate of efficient practices, as is the case in Russia (Avdiushin *et al.*, 1997). Market deregulation can lead to higher energy prices in developing countries and CEITs (Worrell *et al.*, 1997), although efficiency gains may lead to lower costs for some consumers. Small energy or carbon taxes have been implemented for small energy users (including industry) in Denmark and The Netherlands, but it is too early to evaluate the effect on energy use.

New approaches to industrial energy efficiency improvement in industrialized countries include voluntary agreements (VA). A VA generally is a contract between the government (or another regulating agency) and a private company, association of companies or other institution. The content of the agreement may vary. The private partners may promise to attain certain energy efficiency improvement, emission reduction target, or at least try to do so. The government partner may promise to financially support this endeavour, or promise to refrain from other regulating activities. Various countries have adopted VAs directed at energy efficiency improvement (IEA, 1997). Experiences with early environmental VAs varied strongly — from successful actions to limited impacts (Worrell *et al.*, 1997). Voluntary agreements can have some apparent advantages above regulation, in that they may be easier and faster to implement, and may lead to more cost-effective solutions.

Direct subsidies and tax credits or other favourable tax treatments (to raise end-use energy efficiency) have been a traditional approach for promoting activities that are thought to be socially desirable. Incentive programmes need to be carefully justified to assure that social benefits exceed costs. Direct subsidies might also suffer from the ‘free rider’ problem where subsidies are used for investments that would be made anyway. Although evaluation is difficult, estimates of the share of ‘free riders’ in Europe range from 50 to 80% (Farla and Blok, 1995). An example of a financial incentive programme that has had a very large impact on energy efficiency is the energy conservation loan programme that China instituted in 1980. This loan programme is the largest energy efficiency investment programme ever undertaken by any developing country, and commits 7–8% of total energy investment to efficiency, primarily in heavy industry. The programme not only funded projects that on average had a cost of conserved energy well below the cost of new supply, it also stimulated widespread adoption of efficient technologies beyond the relatively small pool of project fund recipients (Levine and Liu, 1990; Liu *et al.*, 1994). The programme contributed to the remarkable decline in the energy intensity of China’s economy. Since 1980 energy consumption has grown at an average rate of 4.8% per year (compared to 7.5% in the 1970s), while GDP has grown twice as fast (9.5% per year), mainly due to falling industrial sector energy intensity. Of the apparent intensity drop in industry in the 1980s, about 10% can be attributed directly to the efficiency investment programme (Sinton and Levine, 1994), and a larger amount from unsubsidised efficiency investments, efficiency improvements incidental to other investments, and housekeeping measures.

Financing in developing countries may be difficult, hindered by high inflation rates, and the need for hard currencies to acquire technologies. Budgets of multilateral financing institutions are relatively small, while bilateral financial assistance schemes may influence the technology selection. The example of the Montreal Protocol Multilateral Fund shows that efficient and effective financing mechanisms can be deployed, although specific barriers may delay the financing schemes. Case-studies have shown that financing schemes for small companies, e.g. soft-loans, subsidies and tax credits, may help to improve the adoption rate (TERI, 1997). Large companies in Newly Industrialized Countries (NICs) seem to have easier access to capital. Trade barriers like import taxes can influence the economic assessment, and hence technology selection and implementation.

### 5.3. *Evaluation and adaptation*

Every industrial facility is unique in the process equipment used, lay-out, resources used, and organisation. Translation from a generic technology level into practical

solutions within a country, sector or individual plant is needed. In UNIDO's National Cleaner Production Programme, it was found that investors only accepted the results of a technology demonstration if these are generated in a situation similar to that of their own. Among other activities, the 'Best Practice' programme in the UK (and replicated in China (Dadi *et al.*, 1997) Brazil, Australia and New Zealand) demonstrates a technology in different industrial applications. Various countries have subsidy programmes under which new applications of existing technologies are eligible. Unless the capacity to adapt technology to the specific circumstances is developed, either in industry or technical assistance providers, investments in cleaner and energy efficient technology will not be successful.

Adaptation of technologies to local conditions is crucial. There is great need for technological innovation for energy efficiency in the developing countries and CEITs. The technical operating environment in these countries is often different from that of industrialised countries. For example, different raw material qualities, lower labour costs, poorer power quality, higher environmental dust loads, and higher temperatures and humidities require different energy efficiency solutions than successful solutions in industrialized country conditions. Technologies that have matured and been perfected for the scale of production, market, and conditions in the industrialised countries may not be the best choice for the smaller scale of production, raw materials used or different operating environments often encountered in a developing country. Transferred technologies seldom reach the designed operational efficiencies, and often deteriorate over their productive life (TERI, 1997) due to several reasons. Improper maintenance, inadequate availability of spare parts and incomplete transfer of 'software' are some of the problems. This stresses the need for effective adaptation strategies, including transfer of technical and managerial skills. Technical training is a very important aspect of a technology transfer (Hassan, 1997), and should preferably be done in the local language.

In practice, adaptation practices vary widely in various countries. For example, Chinese enterprises have spent, on average, only 9 (US) cents on assimilation for every dollar on foreign technology, in contrast to countries as Korea and Japan where the amounts spent on assimilation were greater than those spent on technology itself (Suttmeier, 1997). Countries in later stage of industrialisation may be better equipped for adapting technologies to the local industrial environment, while countries or firms in an earlier stage may (have to) rely more on the foreign suppliers of technology. Equipment suppliers may license part of the construction or parts supply to local firms. This is illustrated by the construction of an advanced steel plant in Korea, which was partly done by Samsung Heavy Industries (Worrell, 1998), as well as examples in the construction of cement

plants in India (Somani and Kothari, 1997), Mexico (Turley, 1995) and Chinese Taipei (Chang, 1994). The examples show a heavy involvement in technology procurement, design and management in close collaboration with the technology suppliers and using the domestic knowledge infrastructure (see above). The Korean and Mexican firms belong to the largest producers in the world of, respectively, steel and cement, and demonstrate the success of using modern technology in industry.

#### 5.4. Repetition

Replication and further development of practices and technologies in developing countries and CEITs is needed. It is also a heavily debated issue involving intellectual property rights (IPRs), and dependence on (foreign) technology suppliers. Many industrial technologies are privately owned, although (part of) the (pre-competitive) research may have been publicly funded. IPR play an important role to ensure recovery of development costs and economic returns to investors and researchers. Strong protection of IPRs can improve technology transfer practices by ensuring economic returns, but also impede further development and transfer if the owner is unwilling to cooperate or if the costs may be prohibitive, especially to developing countries. IPR legislation varies widely across countries and a lack of sufficient protection of IPRs is generally seen as a barrier to technology transfer by technology owners. During the 1990s IPR-legislation has become more internationally harmonised within the GATT-negotiations (IPCC, 2000). A clear (legal) framework is needed to improve adaptation and replication of technology (ESETT, 1991), although it is very complex to determine the right legal framework.

Technology transfer projects need continued support from the technology supplier. This is beneficial to both the technology user and supplier. The user can benefit from experience from other licensees, and the licensor gets an opportunity to gain further market entrance. Experience has shown that reasonable plant performance leads to future business (Hassan, 1997). However, technology owners may be hesitant to share all parts of a technology, including 'software', without sufficient legal protection in the country of the user.

Replication of programmes can help to replicate technologies. Waste minimisation circles started in a few regions in India, and are now replicated in other sectors and regions. UNIDO/UNEP replicated National Cleaner Production Centres in various developing countries and CEITs. Replication of programmes and experiences as a form of South–South co-operation is demonstrated by the transfer of the Indian auditing programme to Jordan. Countries possessing a higher technical capability are faster to replicate and develop a technology. The examples of the FINEX smelt reduction

process development for steelmaking in South Korea (Joo *et al.*, 1998), as well as the development of the HYL direct reduction process for ironmaking in Mexico (Zervas *et al.*, 1996), illustrate the capability of firms in NICs to develop a new process. The advanced FINEX project is an example of technology co-operation between the Austrian supplier and the Korean industry. The steel sector is an industry with relatively frequent and open communication. In other sectors, e.g. the chemicals industry, process and technology knowledge is proprietary, limiting replication and development for developing countries and CEITs. Licensors and contractors are interested in the successful transfer proprietary technology to secure future sales (Hassan, 1997).

Research and development can have various goals, depending on the barriers to be tackled to implement a technology. The challenge of climate change is to achieve deep GHG emission reductions over time, which can only be reached by building (technological) capacity through sustained RD&D efforts. Large potential efficiency improvements do exist on the long term (Blok *et al.*, 1995). A recent US study (DOE, 1995) quotes many successes of energy RD&D. There is consensus among economists that R&D has a payback that is higher than many other investments, and the success of R&D has been shown in fields like civilian aerospace, agriculture and electronics (Nelson, 1982). Still the private sector has a propensity to under invest in RD&D, because it cannot appropriate the full benefits of RD&D investments, due to 'free riders' (Cohen and Noll, 1994). Firms will also under invest in RD&D that reduces costs not reflected in market prices (Williams and Goldemberg, 1995), such as air pollution damages and climate change. The Brazilian Alcohol programme is an example of indigenous technology development. Although, seen as expensive due to relatively lower oil prices since 1986 (Oliveira, 1991; Weiss, 1990), it is seen as a success in the field of technology development. Development has decreased the production costs of alcohol considerably (Goldemberg and Macedo, 1994; Macedo, 1998). Copersucar, a cooperative of sugar and alcohol producers, operates a (leading) joint research centre for agricultural and technology development (Macedo, 1998), as well as training. The centre also maintains a benchmarking programme to monitor and improve performance among members.

## 6. Conclusions and summary

In industry, energy efficiency is often the result of investments in modern equipment, stressing the attention to sound and environmentally benign investment policies. Investments in technology (including hardware and software) in the industrial sector are dominated by the private sector. Recent trends in globalisation of industry seem to affect the international transfer of investments

and technology. FDI is rapidly increasing, although concentrated on a small number of rapidly industrialising countries. FDI is dominated by transnational companies. Although difficult to measure domestic investments in developing countries are still larger than FDI. Official development assistance, although earmarked for low-to-medium income countries, is also concentrated on a few countries. Regular evaluation of the goals of public funding is needed for industrial development with respect to the role of cleaner technologies and with respect to the role of private funds.

Barriers limit the uptake of more efficient technologies. These barriers may include the (un-) willingness to invest in (new) technologies, the level of information and transaction costs, the lack of effective financing (e.g. lack of sufficient funds, high interest), the lack of skilled personnel and a variety of other barriers, e.g. the 'invisibility' of energy and CO<sub>2</sub> emission savings and the lack of inclusion of external costs. Developing countries and CEITs suffer from all of these factors that inhibit market acceptance of technologies plus a multitude of other market problems. Consumers often have no knowledge of energy efficiency (technologies) or cannot afford increases in equipment costs, due to a limited ability to pay increased first costs, limited foreign currency and high inflation rates. A well-developed banking system and existence of appropriate financing mechanisms are essential for the uptake of efficient and cleaner technologies in industry.

Traditionally, technology transfer is seen as a private transaction between two enterprises. However, innovation and technology transfer is an interactive and iterative process, involving many different parties. In a globalising economy and industry ESTs are increasingly facing the same barriers and challenges for implementation around the world. An effective process for technology transfer will require interactivity between various users, producers and adaptors of technology. The variety of stakeholders makes it necessary to have a clear policy framework as part of an industrial policy for technology transfer and co-operation, both for a technology donor and recipient or user. Such a framework may include environmental, energy (international), trade, taxation and, patent legislation as well as a variety of well-aimed incentives. The framework may help to give the right signals to all parties, as well as help to develop innovative concepts for technology assessment, financing, procurement, adaptation, repetition and development. The interactive and dynamic character of technology transfer stresses the need for innovative and flexible approaches, through (long-term) partnerships between various stakeholders, including public-private partnerships.

There is a strong need to develop the capacity to assess and select technologies. Stakeholders in developing countries and CEITs have even more difficult access to technology information, stressing the need for a clearinghouse for information on climate abatement

technology. Various innovative policy concepts, including networking and joint research and information organisations, were found to be successful. To be successful, long-term support for capacity building is essential, stressing the need for public support.

Adaptation of technology to local conditions is essential, but practices vary widely. Countries that spend on average more on adaptation seem to be more successful in technology transfer. As countries industrialise, the technological capabilities increase rapidly, accelerating the speed of technology diffusion and development. This demonstrates that successful technology transfer includes transfer of technological capabilities, which may be beneficial to both the supplier and user. Technology users, suppliers as well as financial institutions and governments need to give attention to adaptation as an essential and integral part of technology procurement.

Technology transfer needs to be incorporated in R&D strategies, as many (public) environmental sound technologies “remain on the shelves” and are not brought into the market as rapidly as may be expected. Several countries and equipment suppliers envisage that environmentally sound product development can enhance the future competition position of domestic suppliers, making technology transfer (through strengthening local capacity and demonstration of technology) a way to open new export markets. Subsequently, policies to support the development of new technologies and markets should be used as part of economic and trade policies.

## Acknowledgements

This paper is a revised version based on work for the IPCC Special Report on Methodological and Technological Issues in Technology Transfer published in the Summer of 2000. We thank the IPCC secretariat for their help. We wish to thank Xiulian Hu (Energy Research Institute, China), Sanghoon Joo (Korea) for their contributions to the IPCC Report and this paper. We also wish to thank Prosanto Pal (TATA Energy Research Institute, India) and Doug McKay (Shell International, UK) for their help with reviewing earlier versions of the IPCC-report. Earlier drafts of the IPCC-report were reviewed by many experts. We thank the reviewers for their help in the preparation of a well balanced report. The work of Ernst Worrell was supported by the Climate Protection Division, Office of Air and Radiation, US Environmental Protection Agency through the US Department of Energy under Contract No. DE-AC03-76SF00098.

## References

- Amsden, A.H., Mourshed, M., 1997. Scientific publications, patents and technological capabilities in late-industrialising countries. *Technology Analysis and Strategic Management* 9(3), 343–359.
- Avdiushin, S., Grtisevich, I., Legro, S., 1997. Climate change mitigation: case studies from Russia. Pacific Northwest National Laboratory, Washington, DC, USA.
- Berkel, R. van, Bouma, J., 1999. Promoting cleaner production investments in developing countries: a status report on key issues and potential strategies. United Nations Environment Programme, Paris, France.
- Blok, K., 1993. The development of industrial CHP in The Netherlands. *Energy Policy* 21(2), 158–175.
- Blok, K., Turkenburg, W.C., Eichhammer, W., Farinelli, U., Johansson, T.B., (Eds.), 1995. Overview of Energy RD&D Options for a Sustainable Future. European Commission, DG-XII, Brussels/Luxembourg.
- Callin, J., Svennesson, B., White, E., 1991. Energy and industrialisation, the choice of technology in the paper and pulp industry in Tanzania. Dept. of Environmental and Energy Systems Studies, Lund University, Lund, Sweden.
- Chang, T.H., 1994. Successful operation of the world's only 5000 tpd short rotary kiln. *World Cement* 25(9), 4–9.
- Chantramonklari, N., 1990. The development of technological and managerial capability in the developing countries. In: Chatterji, M. (Ed.), *Technology Transfer in the Developing Countries*. The Macmillan Press, Ltd., Houndsmill, Hampshire, pp. 36–50.
- Clark, W.W., 1997. The role of publicly-funded research and publicly-owned technologies in the transfer and diffusion of environmentally sound technologies, the case study of the United States of America. Proceedings of International Expert Meeting of CSD on the Role of Publicly-Funded Research and Publicly-Owned Technologies in the Transfer and Diffusion of Environmentally Sound Technologies. Ministry of Foreign Affairs, Republic of Korea, February, 4–6, 1998.
- Cohen, L.R., Noll, R.G., 1994. Privatizing public research. *Scientific American*, September, 72–77.
- Collingwood, J., Goult, D., 1998. The UK energy efficiency best practice programme: evaluation methods & impact 1989–1998. Paper presented at “Industrial Energy Efficiency Policies: Understanding Success and Failure”, Utrecht, The Netherlands, 11–12 June.
- Dadi, Z., Fengqi, Z., Cong, Y., Yingyi, S., Logan, J., 1997. Climate change mitigation: case studies from China. Pacific Northwest National Laboratory, Washington, DC, USA.
- DeCanio, S.J., 1993. Barriers within firms to energy-efficient investments. *Energy Policy* 21, 906–914.
- Department of Energy, 1995. Energy R&D: shaping our nation's future in a competitive world. Task Force on Strategic Energy Research and Development. Department of Energy, Washington, DC, USA.
- Dosi, G., 1988. The nature of the innovative process. In: Dosi, G., Freeman, C., Nelson, R., Silverberg, G., Soete, L. (Eds.), *Technical Change and Economic Theory*. Pinter Publishers, London, UK.
- ESETT, 1991. Symposium Report of the International Symposium on Environmental Sound Energy Technologies and their Transfer to Developing Countries and European Economies in Transition, Milan, 21–25 October.
- Farla, J.C.M., Blok, K., 1995. Energy conservation investment of firms: analysis of investments in energy efficiency in the Netherlands in the 1980's. ACEEE 1995 Summer Study on Energy Efficiency in Industry Proceedings, Washington, DC, USA.
- Fisher, A.C.R., Rothkopf, M., 1989. Market failure and energy policy. *Energy Policy* 17, 397–406.
- Florida, R., 1997. The globalization of R&D: results of a survey of foreign-affiliated R&D laboratories in the USA. *Research Policy* 26, 85–93.
- Gadgil, A., Sastry, A., 1994. Stalled on the road to market: lessons from a project promoting lighting efficiency in India. *Energy Policy* 22, 151–162.

- Gielen, D., 1998. Western European materials as sources and sinks of CO<sub>2</sub>. *Journal of Industrial Ecology* 2(2), 43–62.
- Goldemberg, J. (Ed.), 1998. *The Clean Development Mechanism: Issues and Options*. United Nations Development Programme, New York, USA.
- Goldemberg, J., Macedo, I.C., 1994. Brazilian alcohol program: an overview. *Energy for Sustainable Development* 1(1), 17–22.
- Gruber, E., Brand, M., 1991. Promoting energy conservation in small- and medium-sized companies. *Energy Policy* 19, 279–287.
- Hassan, N., 1997. Successfully transfer HPI proprietary technology. *Hydrocarbon Processing* 76(2), 91–99.
- Hu, X., Jiang, K., Zheng, S., 1998. The potential of energy efficiency improvement in China's iron and steel industry and a case study on technology transfer. *Proceedings of Workshop on Technology Transfer and Innovation in the Energy Sector, STAP/GEF*, 19–20 January, Amsterdam, The Netherlands.
- International Energy Agency, 1994. *Energy Policies of IEA Countries: 1993 Review*. IEA/OECD, Paris, France.
- International Energy Agency, 1997. *Voluntary Actions for Energy-Related CO<sub>2</sub> Abatement*. IEA/OECD, Paris, France.
- International Panel on Climate Change, 2000. *Special Report on Methodological and Technological Issues in Technology Transfer*. Cambridge University Press, Cambridge, UK.
- Jackson, T., 1995. Joint implementation and cost-effectiveness under the framework convention on climate change. *Energy Policy* 23, 117–138.
- Jepma, C.J. (Ed.), 1995. *The Feasibility of Joint Implementation*. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Joo, S., Shin, M.K., Cho, M., Lee, S.D., Lee, J.H., Lee, I.O., Schenk, J.L., Kepplinger, W.L., Wallner, F., Gennari, U.R., Hauzenberger, F., Nagle, M., 1998. Direct use of fine iron ore in the corex® process. *Iron and Steel Maker* 25(7), 39–43.
- Kaplinsky, R., 1997. India's industrial development: an interpretative survey. *World Development* 25(5), 681–694.
- Kuznets, S., 1971. *Economic Growth of Nations: Total Output and Production Structure*. Harvard University Press, Cambridge, MA, USA.
- La Rovere, E.L., 1998. The challenge of limiting Greenhouse gas emissions through activities implemented jointly in developing countries: a Brazilian perspective. *Federal University of Rio de Janeiro, Rio de Janeiro, Brazil*.
- Lee, J., 1997. The maturation and growth of infant industries: the case of Korea. *World Development* 25(8), 1271–1281.
- Levine, M.D., Liu, X., 1990. *Energy conservation programs in the People's Republic of China*. Lawrence Berkeley Laboratory, Berkeley, USA.
- Levine, M.D., Hirst, E., Koomey, J.G., McMahon, J.E., Sanstad, A.H., 1994. *Energy efficiency, market failures, and government policy*. Lawrence Berkeley Lab./Oak Ridge National Lab., Berkeley/Oak Ridge, USA.
- Levine, M.D., Koomey, J.G., Price, L.K., Geller, H., Nadel, S., 1995. Electricity and end-use efficiency: experience with technologies, markets, and policies throughout the world. *Energy* 20, 37–65.
- Little, I.M.D., 1987. Small manufacturing enterprises in developing countries. *World Bank Economic Review* 1(2), 203–236.
- Liu, Z., Sinton, J.E., Yang, F., Levine, M.D., Ting, M., 1994. *Industrial sector energy conservation programs in the People's Republic of China during the seventh five-year plan (1986–1990)*. Lawrence Berkeley National Laboratory, Berkeley, USA.
- Luken, R.A., Freij, A.-C., 1995. Cleaner industrial production in developing countries: market opportunities for developed countries. *Journal of Cleaner Production* 3(1–2), 71–78.
- Macedo, I.C., 1998. The role of copersucar in improving technology for ethanol production from sugar cane in Sao Paulo. *Proceedings of Workshop on Technology Transfer and Innovation in the Energy Sector, STAP/GEF*, 19–20 January, Amsterdam, The Netherlands.
- Muller, M.R., Barnish, T.J., 1998. Evaluation of the former EADC-program. In: Martin, N., Worrell, E., Sandoval, A., Bode, J.-W., Philipsen, D. (Eds.), *Industrial Energy Efficiency Policies: Understanding Success and Failure*. Lawrence Berkeley National Laboratory, Berkeley, CA.
- Nadel, S., 1990. *Lessons learned: a review of utility experience with conservation and load management programs for commercial and industrial customers*. Final Report Prepared for the New York State Energy Research and Development Authority (NYSERDA), the New York State Energy Office, and the Niagara Mohawk Power Corporation, New York, USA.
- Nadel, S., 1991. Electric utility conservation programs: a review of the lessons taught by a decade of program experience. In: Vine, E., Crawley, D. (Eds.), *State of the Art of Energy Efficiency: Future Directions*. American Council for an Energy-Efficient Economy, Washington, DC.
- Nadel, S., Kothari, V., Gopinath, S., 1991. *Opportunities for improving end-use electricity efficiency in India*. American Council for an Energy-Efficient Economy, Washington, DC, USA.
- Nelson, R.R. (Ed.), 1982. *Government and Technical Progress*. Pergamon Press, New York, USA.
- Nelson, K., 1994. Finding and implementing projects that reduce waste. In: Socolow, R.H., Andrews, C., Berkhout, F., Thomas, V. (Eds.), *Industrial Ecology and Global Change*. Cambridge University Press, Cambridge, UK.
- Office of Technology Assessment, 1993. *Industrial Energy Efficiency*. US Government Printing Office, Washington, DC, USA.
- Oliveira, A. de, 1991. Reassessing the Brazilian alcohol programme. *Energy Policy* 19(1), 47–55.
- Pearce, D., 1995. Joint implementation, a general overview. In: Jepma, C.J. (Ed.), *The Feasibility of Joint Implementation*. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Price, L., Michaelis, L., Worrell, E., Khrusch, M., 1998. Sectoral trends and driving forces of global energy use and greenhouse gas emissions. *Mitigation and Adaptation Strategies for Global Change* 3, 263–319.
- Putterman, L., 1997. On the past and future of China's township and village-owned enterprises. *World Development* 25(9), 1639–1655.
- Rama Rao, P., 1997. India: science and technology from ancient time to today. *Technology in Society* 19(3/4), 415–447.
- Reddy, A.K.N., 1991. Barriers to improvements in energy efficiency. *Energy Policy* 19, 953–961.
- Ross, M.H., 1986. Capital budgeting practices of twelve large manufacturers. *Financial Management Winter*, 15–22.
- Sanstad, A.H., Howarth, R.B., 1994. 'Normal' markets, market imperfections and energy efficiency. *Energy Policy* 22, 811–818.
- Sasaki, S., Asuka-Zhang, S., 1997. The role of publicly-funded research and publicly-owned technologies in the transfer and diffusion of environmentally sound technologies, the Japanese study. *Proceedings of International Expert Meeting of CSD on the Role of Publicly-Funded Research and Publicly-Owned Technologies in the Transfer and Diffusion of Environmentally Sound Technologies*, Ministry of Foreign Affairs, Republic of Korea, February 4–6, 1998.
- Schumacher, K., Sathaye, J., 1998. India's pulp and paper industry: evaluation of productivity growth through econometric, statistical and engineering analysis. Lawrence Berkeley National Lab. (Report No.41843), Berkeley, CA, USA.
- Sinton, J.E., Levine, M.D., 1994. Changing energy intensity in Chinese industry. *Energy Policy* 22, 239–255.
- Sioshansi, F.P., 1991. The myths and facts of energy efficiency. *Energy Policy* 19, 231–243.
- Somani, R.A., Kothari, S.S., 1997. Die Neue Zementlinie bei Rajashree Cement in Malkhed/Indien. *ZKG International* 50(8), 430–436.
- Song, J., 1997. Science and technology in China: the engine of rapid economic development. *Technology in Society* 19(3/4), 281–294.

- Sturm, R., Opheim, K., Kelly-Detwiler, P., 1997. The problem of second-hand industrial equipment: reclaiming a missed opportunity. International Institute for Energy Conservation, Washington, DC, USA.
- Suttmeier, R.P., 1997. Emerging innovation networks and changing strategies for industrial technology in China: some observations. *Technology in Society* 19 (3/4), 305–323.
- Syrquin, M., Chenery, H.B., 1988. Patterns of development, 1950–1983. World Bank Discussion Papers No.41, The World Bank, Washington, DC, USA.
- Tata Energy Research Institute (TERI), 1997. Capacity building for technology transfer in the context of climate change. TERI, New Delhi, India.
- Turley, W., 1995. Mexican mammoth. *Rock Products* September 21–25.
- United Nations, 1998. The role of publicly-funded research and publicly-owned technologies in the transfer and diffusion of environmentally sound technologies. UNCTAD, UNEP, DSD, New York, January.
- United Nations Conference on Trade and Development, 1997. World Investment Report 1997, Transnational Corporations, Market Structure and Competition Policy. United Nations, New York and Geneva.
- United Nations Environment Programme, 1997. Environmental management in the pulp and paper industry. UNEP Industry and Environment, Paris, France.
- United Nations Industrial Development Organization, 1997. Industrial Development — Global Report 1997. Oxford University Press, Oxford, UK.
- Velthuisen, J.W., 1995. Determinants of investment in energy conservation. SEO, University of Amsterdam, The Netherlands.
- Warhurst, A., Bridge, G., 1997. Economic liberalisation, innovation, and technology transfer: opportunities for cleaner production in the minerals industry. *Natural Resources Forum* 21(1), 1–12.
- Weiss, C., 1990. Ethyl alcohol as a motor fuel in Brazil, a case study in industrial policy. *Technology in Society* 12(3), 255–282.
- Williams, R.H., Goldemberg, J., 1995. A small carbon users' fee for accelerating energy innovation. Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, USA.
- World Bank, 1997a. The State in a Changing World, World Development Report 1997. Oxford University Press, Oxford, UK.
- World Bank, 1997b. Clear water, blue skies, China's environment in the next century. China 2020 Series, The World Bank, Washington, DC, USA.
- World Bank, 1998. World development indicators 1998. The World Bank, Washington, DC, USA.
- World Energy Council, 1995. Energy efficiency improvement utilising high technology, an assessment of energy use in industry and buildings. World Energy Council, London, UK.
- World Wildlife Fund, 1996. Sustainable energy technology in the South, a report to WWF. Report by Institute of Environmental Studies, Amsterdam, The Netherlands. And Tata Energy Research Institute, New Delhi, India.
- Worrell, E., 1998. Energy efficient technologies in the cement and steel industry — experiences in developing countries. Proceedings of Workshop on Technology Transfer and Innovation in the Energy Sector, STAP/GEF, 19–20 January, Amsterdam, The Netherlands.
- Worrell, E., Levine, M., Price, L., Martin, N., Van Den Broek, R., Blok, K., 1997. Potentials and policy implications of energy and material efficiency improvement. United Nations Division for Sustainable Development, UN, New York.
- Yhdego, M., 1995. Environmental pollution management for Tanzania: towards pollution prevention. *Journal of Cleaner Production* 3(3), 143–151.
- Zervas, T., McMullan, J.T., Williams, B.C., 1996. Gas-Based Direct Reduction Processes for Iron and Steel Production. *International Journal of Energy Research* 20(2), 157–185.